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ABSTRACT

Combined stresses, including both in-plane and out-of-plane stresses, occur in a variety of paper and board converting and end-use applications. Examples include corrugating, supercalendering, adhesive joint formation, printing and tube performance.

Recently, a significant research effort has been directed toward the measurement and prediction of failure envelopes when paper is subjected to combined in-plane stresses. It is believed that the present work is a first attempt to measure the failure envelope of paper when subjected to combined out-of-plane stresses, i.e., out-of-plane shear and normal stresses. It was inspired by one originally developed by Arcan et al. (Experimental Mechanics 18:141-14, 1978) for subjecting composites to combined in-plane stresses.

The above device has been used to determine the effects of refining and wet pressing on the failure envelope of paper. Formette handsheets with a nonrandom fiber orientation were made using a never-dried Southern unbleached kraft pulp. To ensure complete restraint during drying, the handsheets were pressed and dried using the IPST combined press and dryer.

In addition to failure envelope measurements, both in-plane and out-of-plane elastic properties have also been determined. Consideration is also given to predicting the failure envelope of paper when subjected to combined out-of-plane stresses.

INTRODUCTION

The deformation behavior and strength properties of paper are important with respect to its converting and end-use performance. Simple stress situations, e.g., uniaxial tensile, compressive, and simple shear stresses, are important in characterizing a material's deformation behavior; however, in practice, a material such as paper is subjected to more complex stress situations. Examples of converting and end-use performance areas where paper is subjected to complex stresses is shown in Table 1.

Table 1: Examples of converting and end-use performance areas where paper is subjected to complex stresses.

1. Roll Building
2. Corrugating
3. Calendering
4. Printing
5. Molding and Forming Operations
6. Adhesive Joints
7. Paper Tube Performance

In these examples, paper is generally subjected to combinations of both in-plane and out-of-plane stresses. In some instances, failure may occur, e.g., flute fracture in corrugating, adhesive joint failure, and core failure and bursts in roll building. However, even when failure does not occur, the properties of the paper may be modified.

Some progress has recently been made toward measuring and predicting the failure envelope of paper when subjected to combined in-plane stresses (1-4). Furthermore, the failure of paper when subjected to out-of-plane normal and shear stresses has also received attention (5-12). However, the area of combined out-of-plane stresses apparently has yet to be studied.

This contribution is therefore concerned with a device for measuring the failure stress envelope of paper when subjected to combined out-of-plane stresses, and its usefulness in determining how the failure envelope is affected by refining and wet pressing. Consideration will also be given to the prediction of the failure envelope of paper when subjected to combined out-of-plane stresses.

LITERATURE SURVEY

This brief literature survey will be concerned with a review of in-plane shear and combined stress measurements, out-of-plane normal and shear stress measurements, and relevant developments in nonpaper-related fields. Consideration will also be given to failure envelope predictions where appropriate.

In-Plane

In-plane uniaxial tensile measurements on paper are relatively straightforward and routine. By comparison, compressive stress, in-plane shear and combined stress measurements are much more problematic. A number of researchers, including Uesaka et al. (1), de Ruvo and Fellers (2), Hardacker (3), and Gunderson (4), have developed apparatus for combined in-plane stress measurements. Problems include creating a uniform stress field and boundary restraint conditions. Solutions to these problems are evident in the above papers.

Out-of-Plane

Measurement of the out-of-plane deformation behavior of paper is challenging because its thickness dimensions are small, and effective stress transfer to the sample is difficult to achieve without altering its properties. Solutions to the latter problem include two-sided adhesive tape, epoxy adhesives, and photographic mounting tissue.

Out-of-plane shear deformation behavior has been reviewed by the present author (5). Measurement techniques have been developed by Byrd (6), Fellers (7), Heckers, Gottsching (8), and Waterhouse (5). Achieving a pure shear field is difficult, and St. Venant end effects are more serious with an anisotropic material such as paper. Stress concentration effects are also important and more problematic with out-of-plane measurements.

Out-of-plane tensile deformation behavior faces similar challenges to those associated with out-of-plane shear measurements discussed above. Stress concentration problems are particularly important, and paper is considerably weaker in the thickness direction. Procedures for measuring normal or z-direction failure stresses include: Wink and Van Eperen (9), Van Liew (10), Andersson (11), and Hieta et al. (12). A review of z-direction strength measurements has been made by Andersson (11) and Krkoska et al. (13). It is recognized that surface strength measurement (z-direction) is an important related area; however, it will not be considered further in this review.

Out-of-plane measurements are invariably time consuming; however, more rapid techniques include ZDT and tape mullen tests. The success of these methods depends on the adhesive strength of the two-sided tape which is employed. The viscoelastic and flow characteristics of the two-sided adhesive tape are another consideration [Andersson (11)].

No specific measurements of combined out-of-plane stresses on paper appear to have been published. The Scott bond test is primarily a surface strength measurement although it does involve out-of-plane normal, peeling, and shear stresses.

Other Materials

Combined stress measurements have been on materials other than paper. One technique developed by Arcan et al. (14) for in-plane shear and combined stress measurements on composites has been modified by others and applied to plastics, metals, composites, and wood (15,16). The basic design and configuration of the tester, proposed by Arcan et al. (14) and shown in Figure 1, is intended to achieve a uniform stress field. That the design satisfies this condition is verified by strain gauge and photoelastic measurements (14).

Of particular interest to the present study are the combined stress measurements made by Liu and Floeter (15) on wood coupons.

Combinations of pure shear and normal stresses were applied to wood coupons cut parallel and normal to the grain. The failure envelope which was obtained was fit quite well by a tensorial elliptical model.

Since paper is a planar material, it is not possible to directly measure its response to combined out-of-plane stresses on the Arcan et al. device shown in Figure 1. Nevertheless, it was judged that the device could be modified to achieve this objective. Details of this approach and its use in measuring the failure envelope of paper when subjected to combined out-of-plane stresses is given in the sections which follow.

EXPERIMENTAL

The out-of-plane biaxial tester we developed was based on the device developed by Arcan et al. (14) shown in Figure 1. No changes to the basic geometry were made although this may be possible in order to further simplify the design. The major difference between our device and the Arcan et al. fixture is sample geometry and the way it is installed and tested. A comparison of the two methods is shown in Figure 2. The sample size used in the present work is 38.1 mm by 12.7 mm.

The fixture, which was designed for use with a tensile testing machine, is shown installed on an Instron in Figure 3. Also shown in Figure 3 are the sample holder and balancing arms. The six holes at the periphery of the fixture allow for rotation through 15° increments and the application of both normal and shear stresses. In the position shown in Figure 3, the sample is subjected to a pure shear stress.

The sample holder is shown in Figure 4, together with photographic mounting tissues and sample. The sample mounting procedure closely follows that used by the present author (5) for measuring out-of-plane shear deformation behavior of paper. A simple jig is used to align and bond several samples to their holders using photographic mounting tissue. The mounting tissues are heat activated at 120°C using a clamping pressure of 121 kPa. After heat activation and cooling, the samples are normally conditioned at 23°C and 50% RH for 24 hours prior to testing.

Handsheets having a nominal grammage of 300 g/m^2 and a nonrandom fiber orientation were made on IPST's Formette Dynamique. The furnish was an unbleached southern pine kraft pulp having a yield of 65%; it was beaten in a Valley beater to a C.S.F of 660 ml and 430 ml, respectively. After forming and couching, the handsheets, nominally 91 cm by 21.6 cm, were wet pressed and dried between blotters on the IPST press and dryer combination. Three levels of wet press loading were used. The press and dryer combination ensures that the sheets are dried without shrinkage.

After preconditioning and conditioning to TAPPI-recommended procedures of 50% R.H. and 23°C, on-destructive characterization of the handsheets included grammage, hard- and soft-platen caliper measurements (17), and the measurement of in-plane and out-of-plane elastic constants using ultrasonic wave propagation techniques (18,19).

The combined out-of-plane stress measurements reported in this paper were made on machine direction samples only. These samples (38.1 mm by 12.7 mm) were cut from the Formette handsheets, and each sample was again characterized as above prior to mounting. Five measurements were made at each of the six angles for conditions consisting of two levels of refining and three levels of wet pressing.

RESULTS AND DISCUSSION

Nondestructive characterization of the Formette handsheets prior to sample preparation is summarized in Table 2.

The variation of mean in-plane specific elastic constant with apparent density is graphed in Figure 5 for the two refining levels. We see in Table 2 that the in-plane anisotropy R decreases quite considerably with refining even though the forming conditions are held constant. There is also a slight decrease in R with increased wet pressing.

The longitudinal out-of-plane elastic constant variation with apparent density for the two refining levels is shown in Figure 6. In contrast with the in-plane elastic constant variation, we see that the out-of-plane results collapse onto a common line.

The variation of the out-of-plane elastic constants of the individual samples subjected to combined stress measurements, i.e., the average of five samples with apparent density, are graphed in Figures 7 and 8. Again, the elastic constants tend to fall onto a common line, although we now have much more scatter in the data, particularly for the M.D. out-of-plane shear elastic constant.

The variation in failure stress with apparent density from pure shear to pure normal or z-direction stress in 15-degree increments is graphed in Figures 9 through 14. Regression lines are also shown in these figures, and for most angles, a reasonable degree of correlation is found. Furthermore, the data points for the two levels of refining appear to collapse onto a common regression line which is consistent with the elastic behavior.

From these results, the variation of failure stress with angle is shown in Figure 15 for three levels of densification, i.e., 0.5, 0.6, and 0.7 g/cm^3. The solid lines shown in Figure 15 are predictions calculated using equation 1 given below. The agreement appears to be quite good, considering the high variability which can arise with this type of measurement, i.e., typically around 15%.

Equation 1 follows a similar form of prediction based on tensor polynomial theory made by Liu and Floeter (15) for the combined shear and normal stress failure of Sitka spruce wood veneers. Liu and Floeter prepared butterfly-type wood veneers normal to and across the grain for biaxial stressing using the Arcan et al. device in the in-plane mode (see Figure 2).

$$\sigma^2_f(\theta) = \frac{\sigma^2_s x \sigma^2_n}{\sigma^2_s x \cos^2\theta + \sigma^2_n x \sin^2\theta} \qquad (1)$$

where $\sigma_f(\theta)$ is the failure stress at any angle θ to the pure shear stress axis and σ_s and σ_n are the pure shear and normal stresses, respectively.

CONCLUSIONS

An out-of-plane biaxial stressing device has been designed and built for measuring the failure envelope of paper subjected to combined out-of-plane normal and shear stresses. The device has been used to determine the failure envelope of handsheets made from a 65%-yield unbleached southern pine kraft pulp with a nonrandom fiber orientation produced at two levels of refining and three levels of wet pressing. It was found that the failure envelopes were largely independent of the mode of densification, i.e., levels of refining and wet pressing. Reasonable agreement was also found between the measured and predicted failure envelope based on a modified form of tensor polynomial theory. The failure envelope is elliptical.

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Table 2: Summary of Formette Handsheet Properties.

Grammage g/m^2	Caliper μm	Density g/cm^3	E/rho (k/sec)	R(=Emd/Ecd)	Ez/rho $(k/sec)^2$	Exz/rho $(k/sec)^2$	Eyz/rho $(k/sec)^2$
C.S.F. = 660 ml							
313	642	0.487	6.51	2.26	0.144	0.236	0.151
310	454	0.682	7.46	2.11	0.226	0.278	0.201
312	411	0.759	7.79	2.13	0.264	0.266	0.211
C.S.F. = 430 ml							
299	557	0.537	7.13	1.75	0.163	0.269	0.178
288	395	0.730	8.29	1.71	0.245	0.300	0.239
295	371	0.796	8.50	1.71	0.265	0.334	0.270

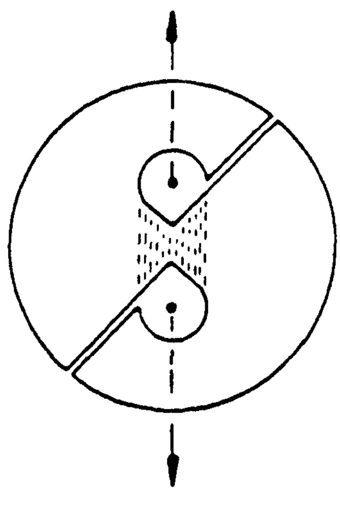


Figure 1: Basic configuration of in-plane tester proposed by Arcan et al. (14).

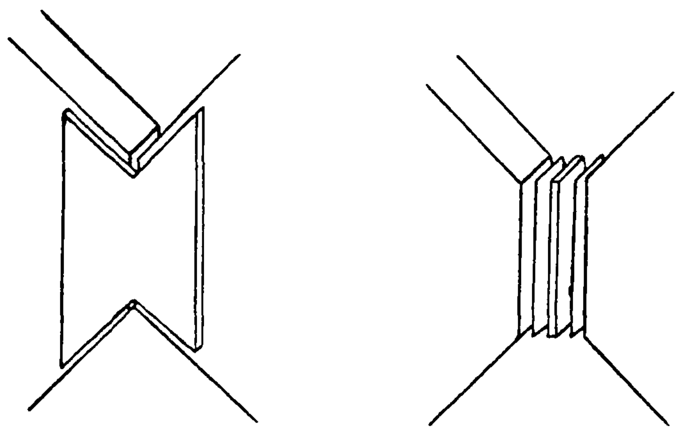
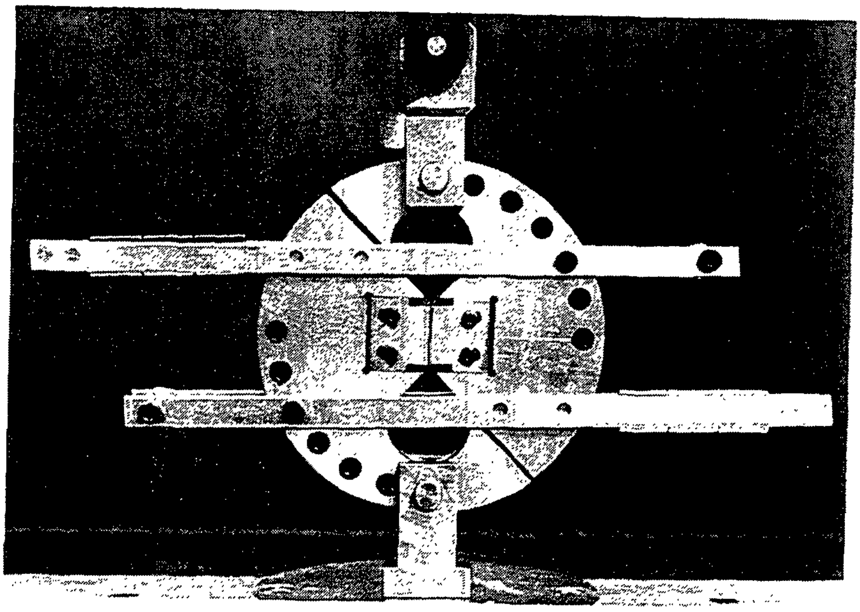


Figure 2: Comparison of sample mounting positions for in-plane and out-of-plane biaxial testing.



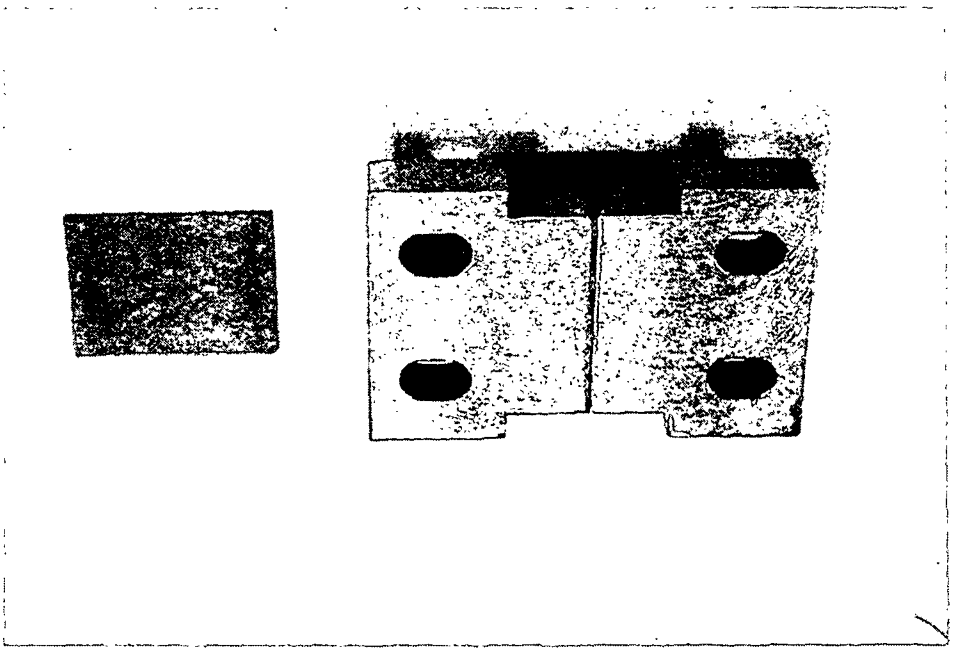


Figure 4: Sample holder, sample, and photographic mounting tissues.

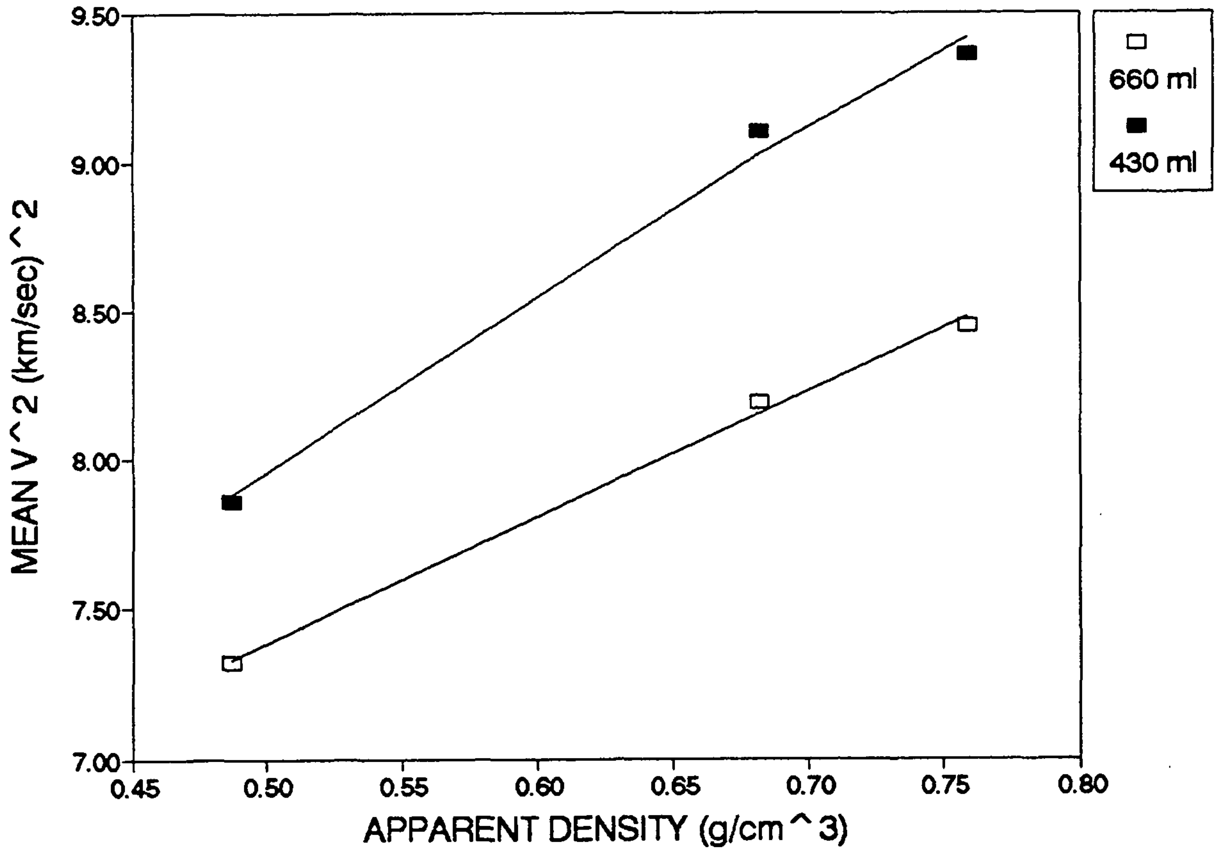


Figure 5: Variation of mean in-plane specific elastic constant for two levels of refining.

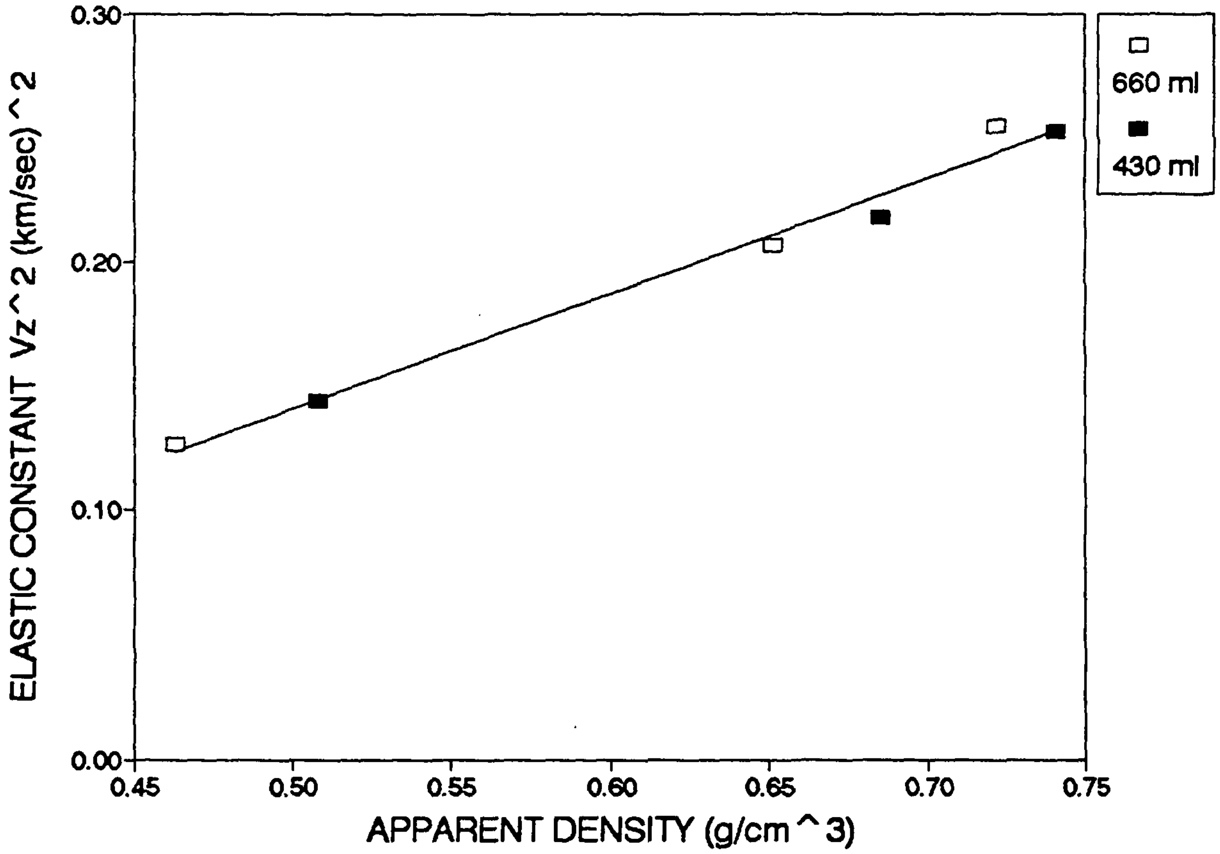


Figure 6: Variation of out-of-plane specific elastic constant with apparent density for two levels of refining.

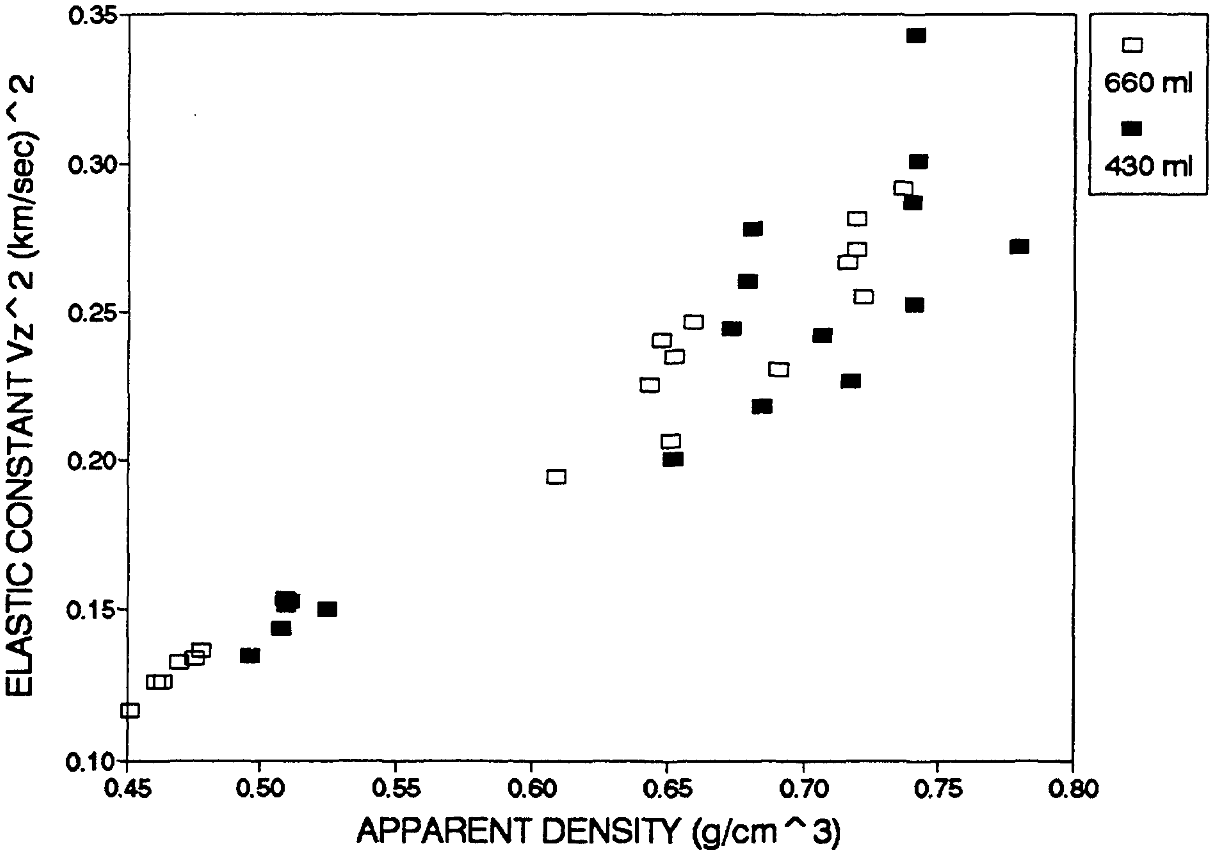


Figure 7: Variation of out-of-plane specific elastic constant with apparent density for two levels of refining —38.1 mm x 12.7 mm samples.

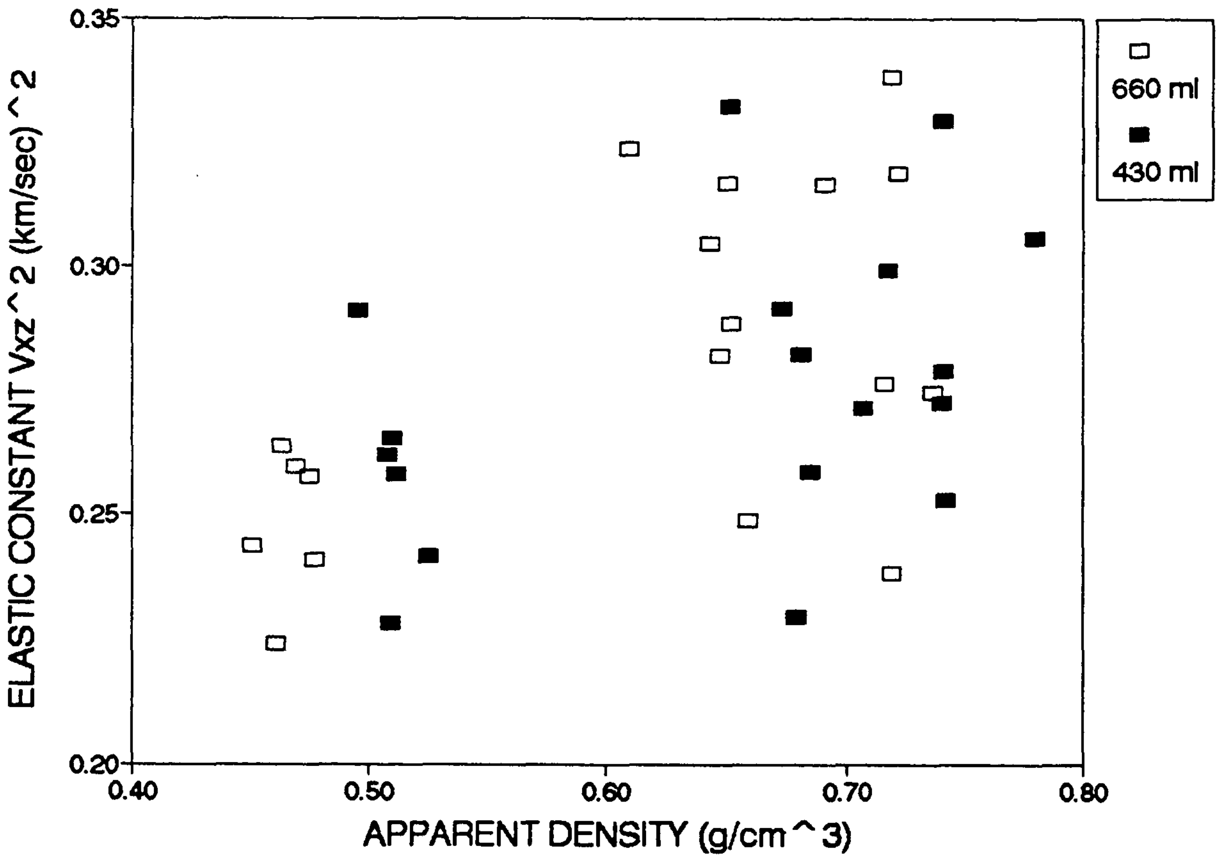


Figure 8: Variation of out-of-plane specific shear elastic constant with apparent density for two levels of refining —38.1 mm x 12.7 mm samples.

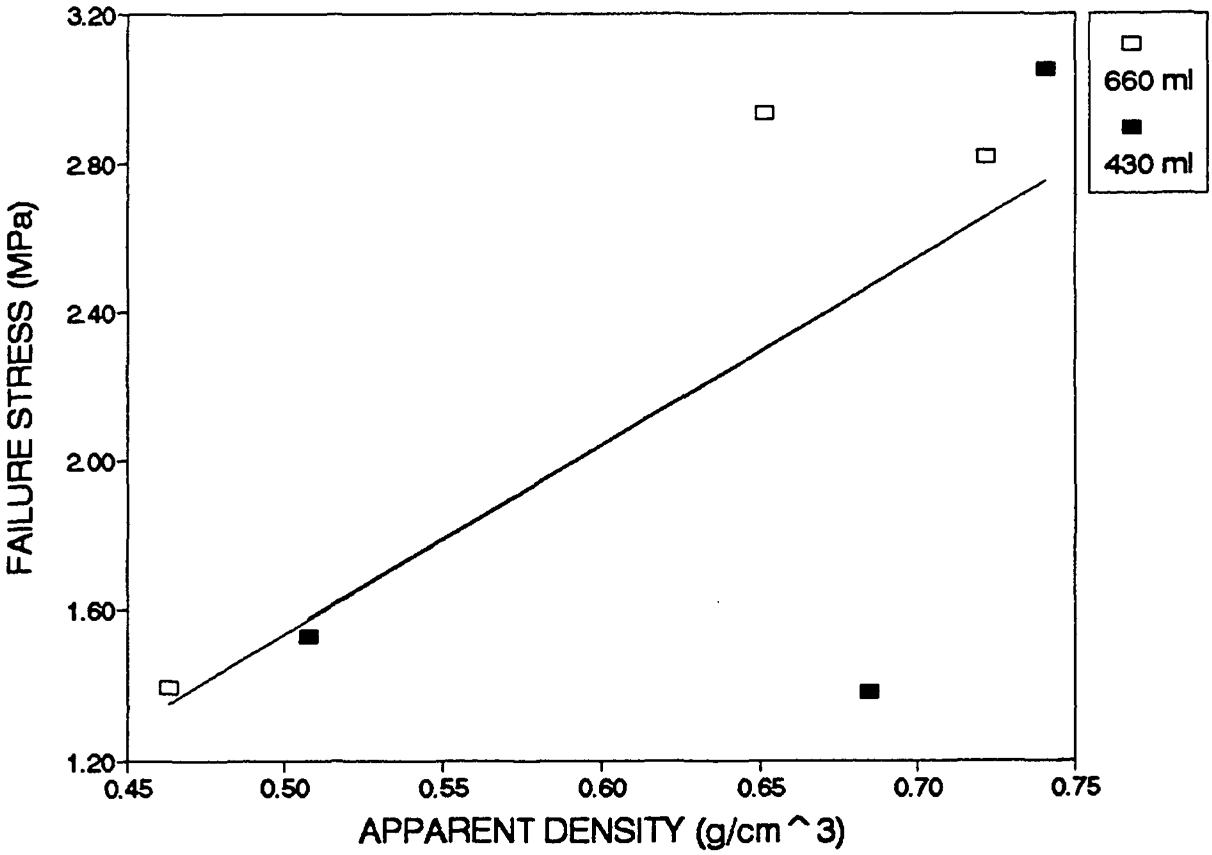


Figure 9: Variation of failure stress with apparent density—$\theta = 90°$ (Pure Shear Stress).

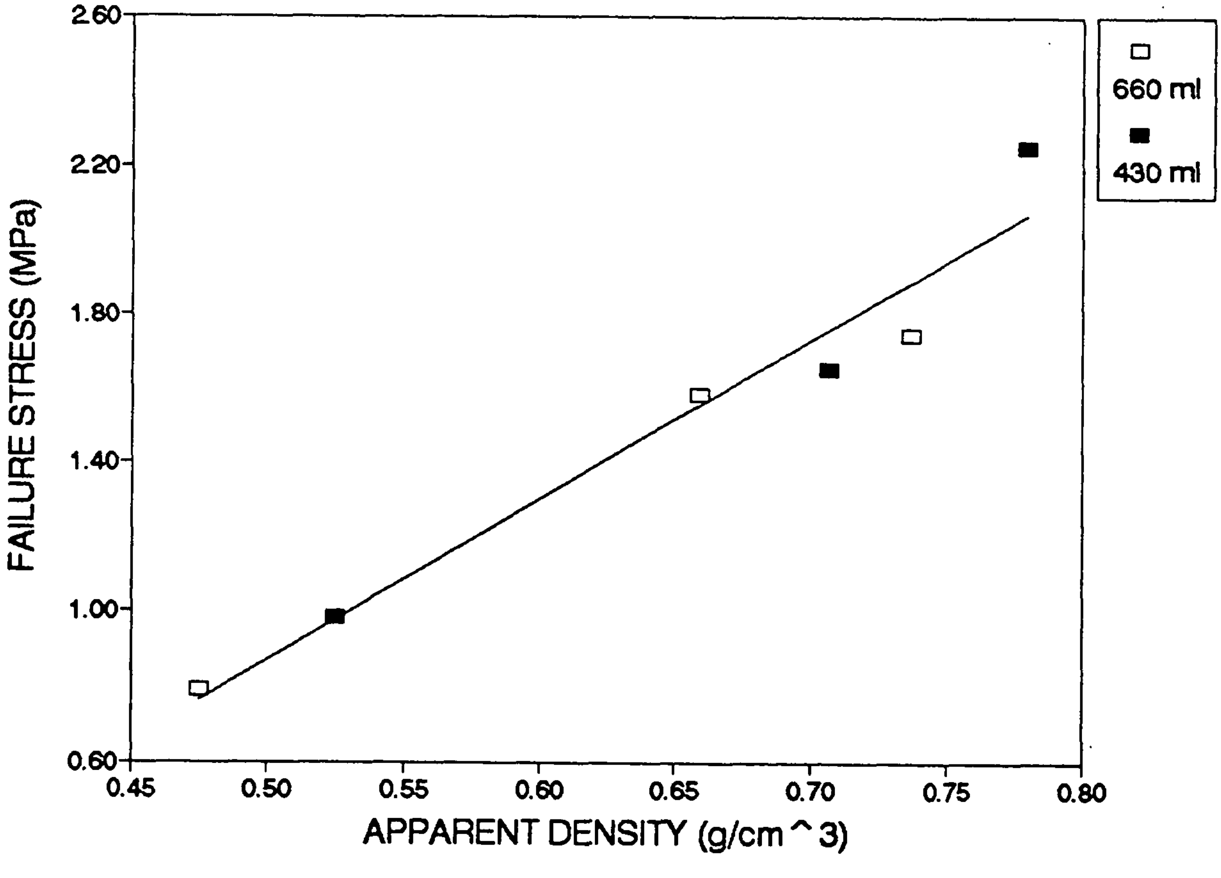


Figure 10: Variation of failure stress with apparent density—$\theta = 75°$.

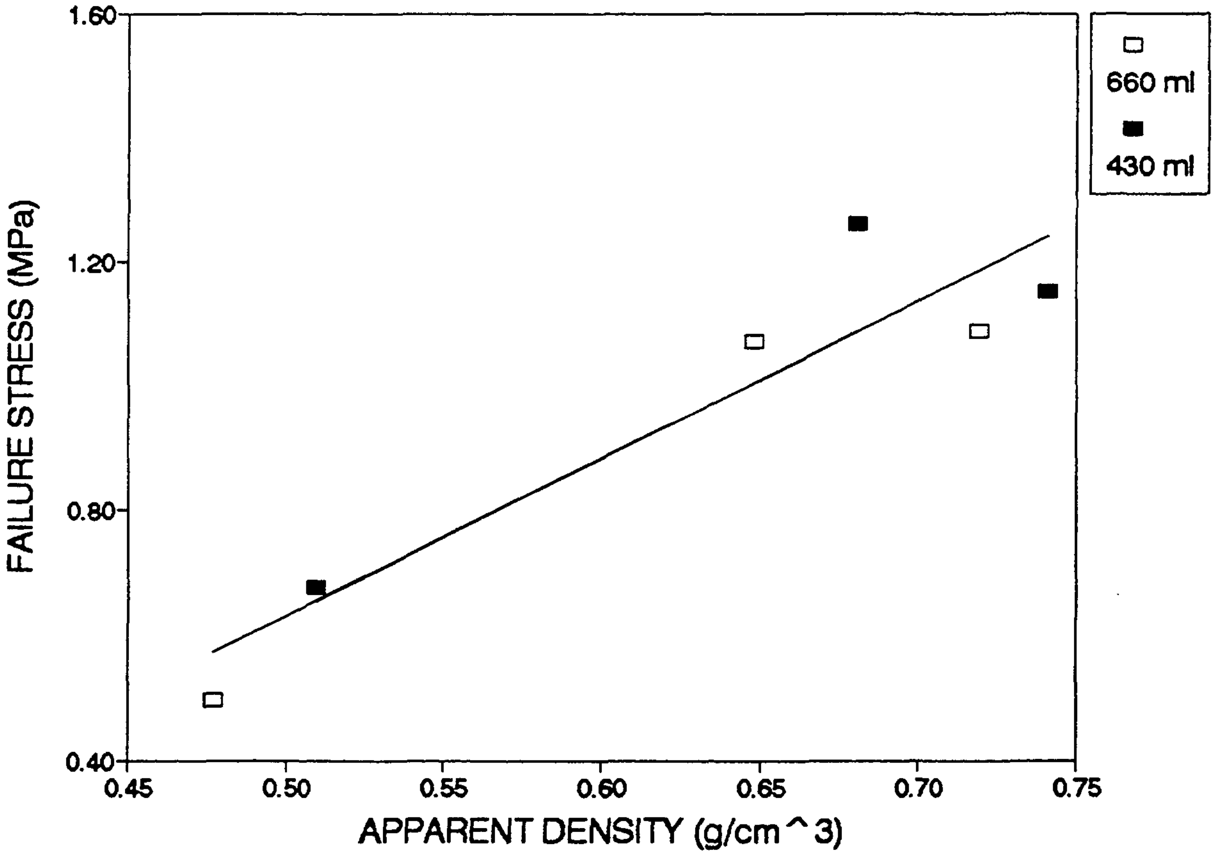


Figure 11: Variation of failure stress with apparent density—$\theta = 60°$.

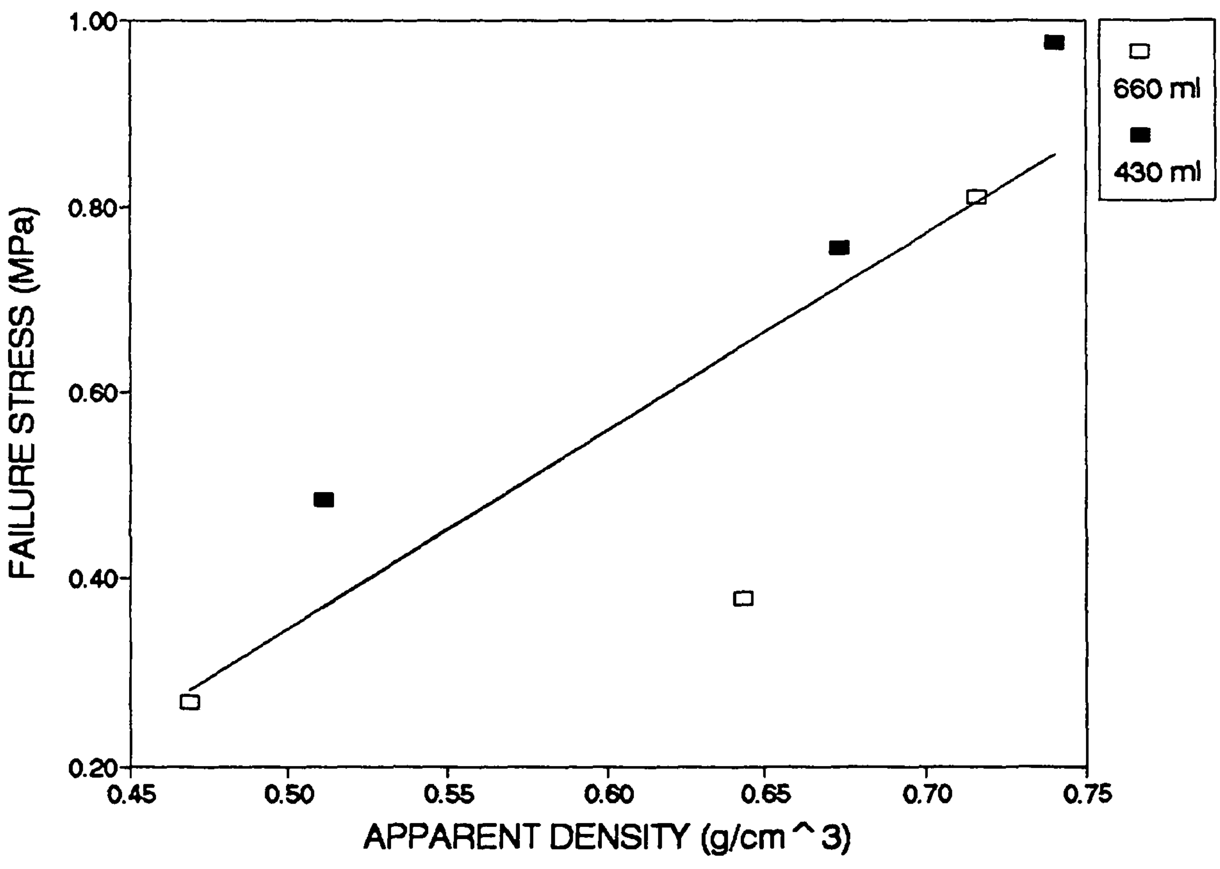


Figure 12: Variation of failure stress with apparent density—$\theta = 45°$.

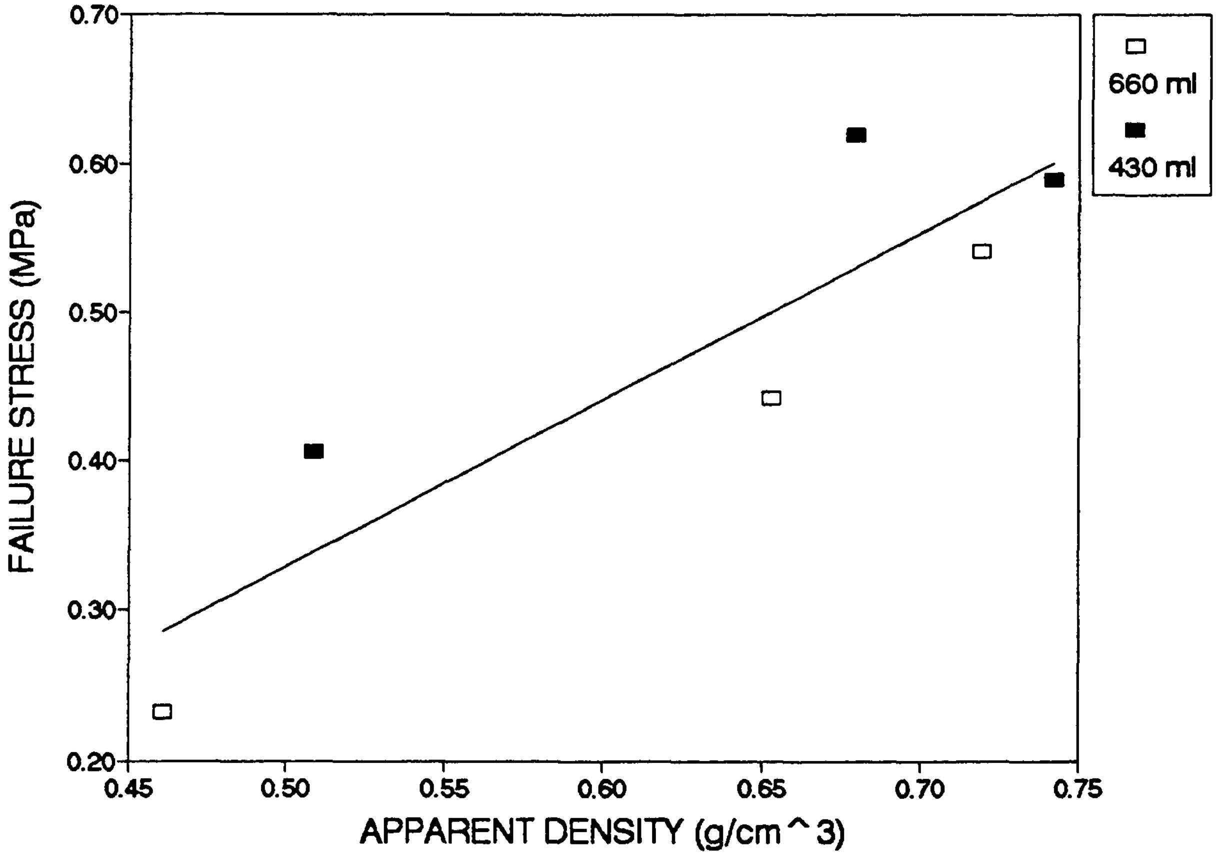


Figure 13: Variation of failure stress with apparent density—θ = 30°.

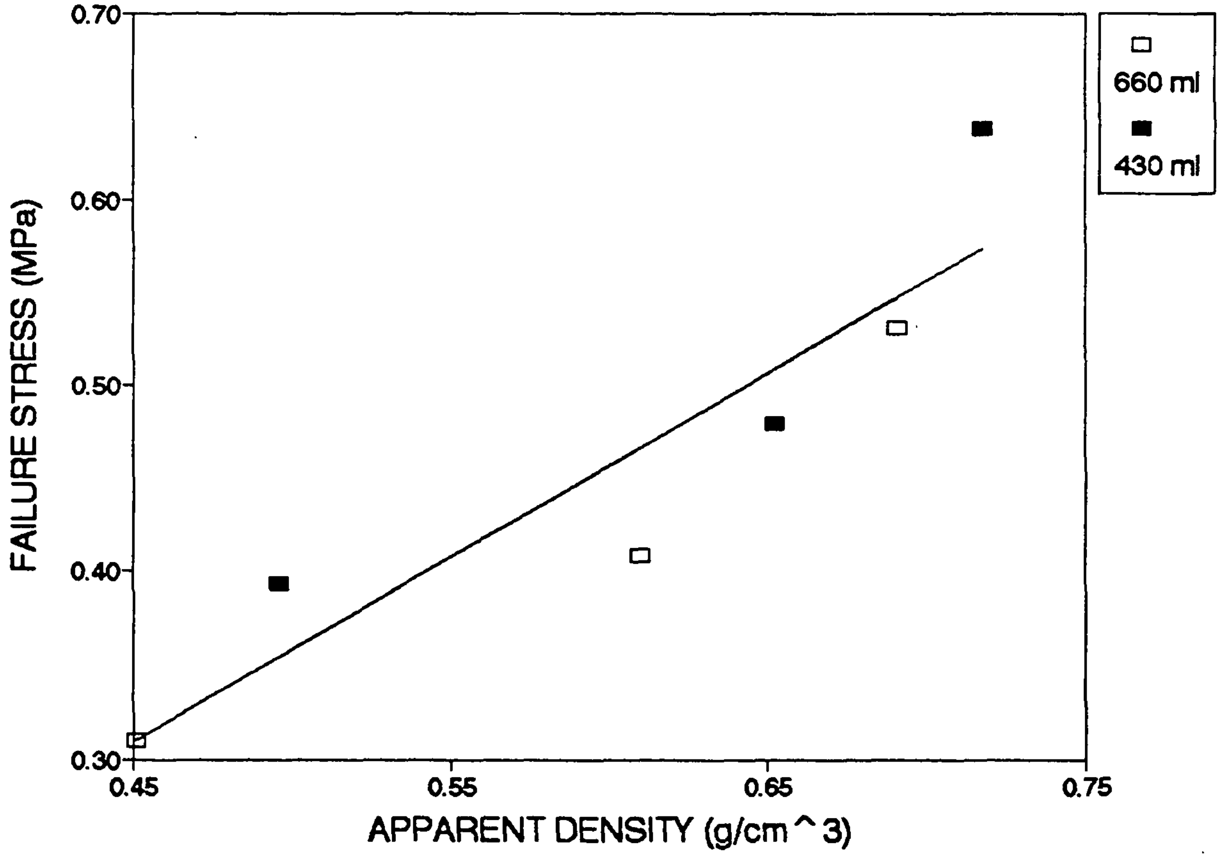


Figure 14: Variation of failure stress with apparent density—$\theta = 0°$ (Pure Normal Stress).

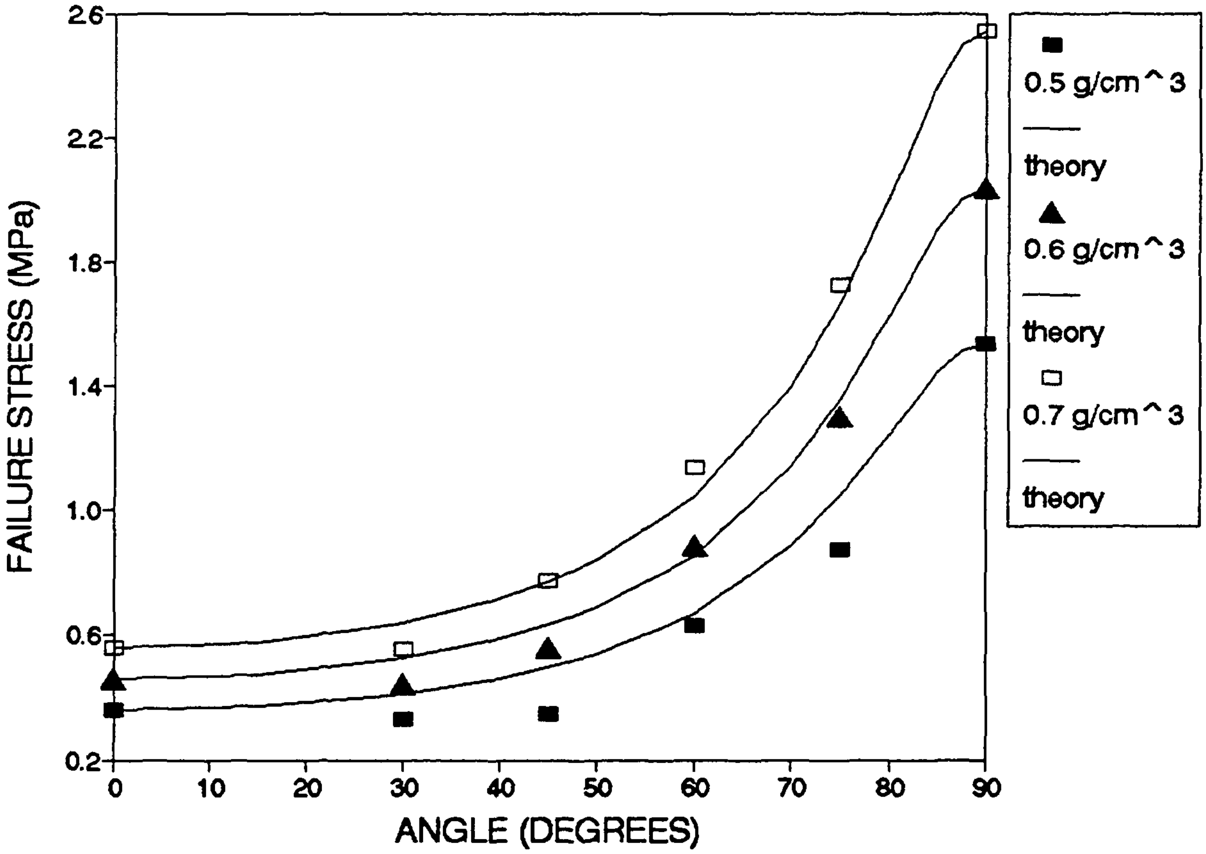


Figure 15: Variation of failure stress with angle θ° for three levels of densification.